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DESMATICS, INC.

P. O. Box 618
State College, Pa. 16801
Phone: (814) 238-9621

Applied Research in Statistics - Mathematics - Operations Research

FINAL REPORT

STATISTICAL RESEARCH ON PROBLEMS ASSOCIATED WITH NAVY IMPACT ACCELERATION AND SHIP MOTION PROGRAMS

by

Dennis E. Smith

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I. INTRODUCTION

This final technical report on Contract No. N00014-74-C-0154 summarizes a research investigation conducted by Desmatics, Inc. under sponsorship of the Office of Naval Research. The Desmatics study has been devoted to statistical research in a number of problem areas associated with the impact acceleration and ship motion programs being conducted by the Naval Aerospace Medical Research Laboratory (NAMRL) Detachment.

The following section of this report briefly reviews research results in the main problem areas addressed by Desmatics. The final section provides a reference list of technical reports and other publications prepared under this contract.

II. RESEARCH RESULTS

During the technical effort performed under Contract No. N00014-74-C-0154, Desmatics has conducted statistical research associated with NAMRL impact acceleration and ship motion programs. The following paragraphs, which review research results, briefly describe the three primary problem areas considered by Desmatics.

A. HEAD/NECK DYNAMIC RESPONSE MODEL

A portion of the Desmatics technical effort has been devoted to development of a predictive model of dynamic response of the human head/neck system to $-G_x$ impact acceleration. This model, based on empirical data only, requires no assumptions about the mechanical structure of the system. It predicts the time-varying inertial response of the unrestrained human head to $-G_x$ impact acceleration. Using the linear acceleration time profile of neck (T_1 vertebra) motion as input information, the model produces time profiles for the accelerations at the head center of gravity.

Model development (i.e., estimation of all required model parameters) was based upon data from NAMRL impact acceleration experiments. In these experiments, volunteer subjects were strapped securely to a steel chair rigidly mounted on a sled. During sled acceleration, the subject's motion was measured by instrumentation which included two accelerometer arrays: one located at the mouth, and the other on the posterior spinous process of the first thoracic vertebra (T_1).

Model parameters were estimated using the data from six instrumented human volunteers, who were each exposed to a number of $-G_x$ impact accelerations.

Data from a total of 24 tests was used to estimate the required parameters.

The basic model, representing a group of six individuals, was developed using the linear X acceleration measured at vertebra T_1 as the input, the linear X and Z accelerations and angular Y acceleration of the head CG as outputs. Then, for a second independent set of 24 impact runs the model was used to predict the head accelerations produced by each T_1 acceleration. In each instance, the model's response was visually compared with the actual response measured from the subject. In general, the model and measured responses were in good agreement, approximately as good as the agreement between the responses of the same subject undergoing two identical impact accelerations. This "eyeball" evaluation was augmented with a statistical analysis of model performance based on F-tests designed to test model bias.

From evaluation of model performance, which was based on data independent of that used in model development, it was found that variations between model output and measured head response were comparable to variations between the head responses of subjects undergoing the same impact accelerations. This indicates that the model will be useful in subsequent studies of human response to impact acceleration.

A study of model sensitivity to design changes suggests that, based on the available evidence, the selected model is a satisfactory compromise between performance and simplicity. In addition to its relatively good performance, the model has the advantage that its development is based only on observed inertial response data. Model accuracy is, therefore, not dependent on often hypothetical parameters defining the mechanical structure of the head/neck dynamic system.

This aspect of the Desmatics research has been discussed in technical

presentations [2,5] at two scientific meetings and in a journal article [8].

B. IMPACT ACCELERATION INJURY PREDICTION MODEL

The Desmatics research effort has also been devoted to investigation of head/neck injury prediction models for the impact acceleration environment. The general framework of a statistical model has been discussed in two technical reports [1,3]. The resulting model may be used to predict the probability of head/neck injury. As a basis for discussing the model, consider the impact acceleration situation in which the torso is well-restrained, but the head and neck are unrestrained. In this situation the problem is one of predicting whether a human of given anthropometric characteristics will sustain injury if exposed to impact acceleration which results in given dynamic response of the head/neck system. A number of difficulties must be overcome to develop an injury prediction model from empirical data. If enough instrumented human subjects were available, and could be subjected to various acceleration time traces, a reasonable prediction model would eventually result. Of course, this procedure is not possible--human subjects cannot be purposely injured.

In any event, it must be realized that the situation is not deterministic. For example, even with a restrained torso, the same impact acceleration will result in different head/neck response (for example, because of initial head position), and even apparently identical head response for the same person may result in injury sometimes and not at other times. This binomial aspect of injury occurrence defines a discrete random variable which must be considered. To further complicate matters, the acceleration and dynamic response data under consideration is time trace data.

Because dealing with the complete acceleration time traces of the head

is an impossible analytic task, a set of univariate head dynamic response variables which may be expected to be related to injury should be considered. Likely candidates include, for example, linear and angular velocities and accelerations (average or peak). Although a number of anthropometric variables can also be postulated, it is probably reasonable to assume that their effect within a species will be minor when compared to that of the dynamic response variables. Thus, it is suggested that only these latter variables be considered in initial model development. At a later stage, the anthropometric variables should prove important in scaling.

In general, then, a set of k variables, which will be denoted by $\underline{x} = (x_1,\ldots,x_k)$, is being considered. It is postulated that the probability of injury is some (unknown) function of these variables. Furthermore, although the function is unknown, it will be near zero in part of $\underline{x}$-space, near one in another part, and will increase from near zero to near one over an intermediate part. Experimentally what is observed in a given situation is only an estimated value (either 0 or 1) of the true probability.

In summary, the probability of injury is being considered as a function of $\underline{x}$. Thus, this probability may be denoted by:

$$P = P(\underline{x}) = P(x_1,\ldots,x_k).$$

Furthermore, the observed value of P will be denoted by y, where:

$$y = \begin{cases} 1 \text{ if an injury is sustained} \\ 0 \text{ if no injury is sustained.} \end{cases}$$

It will be assumed that a logistic function provides a reasonable approximation to the function defining probability. The logistic function

is given by:

$$P(\underline{x}) = \{1 + \exp[-(\beta_0 + \sum_1^k \beta_i x_i)]\}^{-1}$$

When this function is used, all predicted probabilities are restricted to the range (0,1). Furthermore, this function satisfies the conditions of being near zero in a part of $\underline{x}$-space, near one in another part, and increasing from near zero to near one over an intermediate part. It is also tractable computationally.

From a set of observed data, the coefficients (i.e., $\beta_0, \beta_1, \ldots, \beta_k$) of the logistic model may be estimated. The estimation process is fairly complex, involving an iterative procedure which provides the maximum likelihood estimates. This does not pose an insurmountable problem, however, since the computer is available.

Nonetheless, the data input to a model of this kind is of necessity dichotomous, requiring the use of larger samples than required to obtain a desired degree of predictive accuracy if the data were continuous. Thus, it is of central concern to investigate the degree of accuracy which may be expected for predictions derived from the model, and to examine the sensitivity of such predictions to sample size.

A Monte Carlo simulation study was undertaken to provide information relating accuracy to sample size for selected model configurations. Two specific sets of model parameters were considered, Monte Carlo samples of various sizes were generated for each, and the accuracy of the resultant predictions were evaluated with respect to the true probabilities. This study is described in a Desmatics technical report [9].

Research has also been focused on applications to real data and on

statistical inferences based on model results. A recent technical report [10] and technical presentation [7] considered application of a logistic model to observed data from a set of twenty-eight $-G_x$ accelerator runs involving subhuman primates (Rhesus monkeys) with securely restrained torso and unrestrained head. The data was collected by the Naval Aerospace Medical Research Laboratory (NAMRL) Detachment as part of its research effort on acceleration impact injury prevention.

Two prediction models were constructed from this data, one based on head dynamic response only and the other based on sled acceleration profile only. The first model was derived from three variables distilled from head dynamic response time trace data. These three variables were:

(1) peak head angular acceleration (resultant) measured in radians/sec^2,

(2) peak head linear acceleration (resultant) measured in meters/sec^2,

and (3) peak head angular velocity (resultant) measured in radians/sec.

The second model was based on two variables describing sled acceleration:

(1) peak sled acceleration measured in G's

and (2) rate of sled acceleration onset measured in G/sec.

Surprisingly, the model based on sled profile variables provided better predictions than the model based on head dynamic response variables. Because of this, both sets of variables were combined into one overall five-variable set, which was then used in development of a prediction model. It was found that, for the relatively small amount of data available, inclusion of peak sled acceleration and any one of the other variables

resulted in a model which yielded predictions in almost perfect agreement with the observations.

Since it is intuitive that a model based on head dynamic response should provide predictions which are as good as or better than those from a model based on sled profile, some explanation is required. There are a few possible reasons for this anomalous result. It may be that the wrong variables were extracted from the head dynamic response time traces, and other variables would have more correctly conveyed the information within these time traces. On the other hand, the correct variables may have been selected but errors may have been present in their measurement. In addition, it is possible that the small sample size resulted in a spurious result.

It must be realized, however, that consideration of any of the three head dynamic response variables in conjunction with peak sled acceleration provides a perfectly fitting model. Thus, there is evidence that head dynamic response variables and sled profile variables may be used together to provide good results. Nonetheless, it is still an open question of why head dynamic response variables alone did not provide a model which performed as well as the one based on sled profile variables alone. Further research on this topic should prove valuable.

Additional research has been concerned with statistical inferences about $\underline{\beta}$, the parameter vector of the logistic model, and $P(\underline{x})$, the true probability of injury corresponding to acceleration variables $\underline{x}$. Because confidence interval estimates and hypothesis tests about $\underline{\beta}$ and $P(\underline{x})$ are sensitive to the variability in the estimated parameter vector $\underline{\beta}$, attention has been directed to them.

Inferences of much importance deal with the assessment of $P(\underline{x})$. Such

inferences can be made by the prediction of critical envelopes and by testing relevant hypotheses. A critical envelope may be defined as the set of all combinations of $\underline{x}$ for which the predicted probability of injury is less than some given amount. However, because variability in the predicted probability causes error variability in the predicted critical envelope, this must be taken into account in the prediction process.

In addition to the use of critical envelopes, hypothesis tests can be conducted to draw inferences of $P(\underline{x})$ in relation to some small probability of injury, P_0. The statistical structure of hypothesis testing can be used to control the probability of making a wrong decision concerning the relationship of $P(\underline{x})$ to P_0.

Pertinent statistical inference procedures have been discussed in a recent technical report [11]. In addition, a Bayesian approach to these inferences has also been explored [12]. A Bayesian approach incorporates prior information with sample information by the use of a prior probability distribution. This distribution can be used to quantify an experimenter's prior beliefs and expert knowledge about an experiment.

C. EVALUATION OF MOTION SICKNESS PREDICTION MODELS

A third area of research has been concerned with statistical problems related to the investigation of ship motion effects on humans. One goal of this investigation is to predict motion sickness incidence (MSI) associated with complex motion characteristic of Navy ships at sea. Other researchers have defined MSI as the probability of emesis, and have developed two MSI predictive models, but only for sinusoidal motion.

Both of these models appear to yield relatively accurate MSI predictions

in those cases where motion is defined by a single sinusoid. However, neither model can be used directly in predicting MSI for ship motion, because that motion tends to be broadband. Desmatics has examined three approaches for obtaining such predictions in light of the observed MSI data from an experiment in which subjects were exposed for two hours to motion produced by the sum of two sinusoids. These three approaches may be referred to as (1) the independent effects approach, (2) the weighting approach, and (3) the least squares weighting approach.

The independent effects approach assumes that when motion results from a combination of sinusoids, there is no interaction (i.e., synergism) between them relative to MSI. The second approach, analogous to A-weighting in acoustics, involves weighting all frequencies back to a single frequency f_0. The frequency f_0 is defined as the "most critical frequency", that is, the frequency which results in the largest MSI prediction.

The third approach, like the previous one, also weights all frequencies back to a single frequency f_0. However, whereas the previous approach specifies the weights a priori based on an existing sinusoid model, the empirical least squares weighting approach determines them a posteriori from experimental MSI data resulting from motion corresponding to complex waveforms. Thus, this approach, unlike the other two, requires access to MSI data from motion that is other than sinusoidal.

Under the hypothesis that a given approach results in the prediction of the true MSI value (denoted by MSI_0) for a duration of two hours under specific motion conditions,

$$z = \frac{x - n(MSI_0)}{\sqrt{n(MSI_0)(1 - MSI_0)}}$$

would be approximately distributed as a standard normal random variable, where

n = the number of subjects observed under this motion condition

and

x = the number of subjects who were overcome by emesis within two hours.

Based on the observed values of z calculated from the experimental data, a test of the hypothesis may be made. However, when a number of tests are made, the problem of multi-test bias arises. Multi-test bias refers to the phenomenon that as the number of tests made increases, the chances of making at least one type I error also increases. To avoid this sort of contamination, it is desirable to use a single overall test.

Such a test may be based on the statistic

$$X = -2 \sum_{i=1}^{N} \ln(p_i)$$

where p_i denotes the probability of the observed outcome of the $i^{\underline{th}}$ individual test in a total of N tests. Under the hypothesis, the statistic X has an approximate Chi-square distribution with 2N degrees of freedom. The results of this test shed serious doubt on the usefulness of both the independent effects approach and the weighting approach as methods of predicting MSI. Tests of the least squares weighting approach are inappropriate and therefore were not performed. For that approach, extremely good agreement between observed and predicted MSI values is to be expected because two weights were estimated based on a total of only three observations. Furthermore, predicted MSI values would be compared with the observed MSI values from which the weights had been estimated. A valid test of this approach

would require a larger set of observed data.

Although only a small amount of empirical MSI data exists for motion other than that produced by a single sinusoid, that data provides a strong indication that neither the independent effects approach nor the weighting approach produces accurate MSI prediction. (Judgment about the least squares weighting approach must be reserved until enough empirical data exists to provide an adequate test.) Details of the statistical analysis of the MSI data are given in a Desmatics technical report [6].

III. REFERENCES

The following is a chronological list of technical reports and other publications prepared under Contract No. N00014-74-C-0154:

[1] Smith, D. E., "Research on Human Impact Acceleration Dynamic Response and Injury: Some Statistical Aspects of Modeling", Technical Report No. 102-1, December 1974.

[2] Smith, D. E., and Anderson, W. R., "A Linear Model of the Human Head/Neck Systems for $-G_x$ Impact Acceleration", Aerospace Medical Association Annual Meeting, April 1975.

[3] Smith, D. E., "Research on Construction of a Statistical Model for Predicting Impact Acceleration Injury", Technical Report No. 102-2, February 1976.

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[5] Smith, D. E., and Anderson, W. R., "Development and Validation of a Predictive Model of Dynamic Response of the Head/Neck System in the $-G_x$ Impact Acceleration Environment", Symposium on Biodynamic Models and Their Applications, February 1977.

[6] Smith, D. E., "Prediction of Motion Sickness Incidence: A Statistical Examination of Three Approaches", Technical Report No. 102-4, August 1977.

[7] Smith, D. E., "The Structure of a Statistical Model for Predicting Impact Acceleration Injury", The Neuroelectric Society Annual Meeting, December 1977.

[8] Smith, D. E., and Anderson, W. R., "Predictive Model of Dynamic Response of the Human Head/Neck System to $-G_x$ Impact Acceleration", Aviation, Space, and Environmental Medicine, January 1978.

[9] Smith, D. E. and Gardner, R. L., "A Study of Estimation Accuracy When Using a Logistic Model for Prediction of Impact Acceleration Injury", Technical Report No. 102-5, March 1978.

[10] Smith, D. E., "An Examination of Statistical Impact Acceleration Injury Prediction Models Based on $-G_x$ Accelerator Data for Subhuman Primates", Technical Report No. 102-6, August 1978.

[11] Peterson, J. J., and Smith, D. E., "Statistical Inference Procedures for a Logistic Impact Acceleration Injury Prediction Model", Technical Report No. 102-7, December 1978.

[12] Peterson, J. J., and Smith, D. E., "Some Bayesian Inference Procedures for Use in Developing an Impact Acceleration Injury Prediction Model", Technical Report No. 102-8, March 1979.

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